

Scalar Mesons and Chiral Dynamics

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Abstract

We discuss scalar mesons properties on the light of chiral dynamics. Considering them as the chiral partners of pseudo-scalar mesons we propose an explanation to their unusual properties based on non-trivial vacuum effects coming from the interplay between spontaneous breaking of chiral symmetry and the violation of $U_A(1)$ symmetry by instantons. Including vector mesons as external sources we work out predictions for radiative decays of vector mesons and compare some of them with recent experimental results from high luminosity Φ factories.

I. INTRODUCTION

The understanding of scalar excitations is a fundamental problem which we encounter in many branches of physics ranging from the dilaton in theories for gravity, the higgs in the electroweak theory, to the pairing of fermions in condensed matter. The reason is quite simple: scalar excitations have the same quantum numbers as the vacuum and their properties are strongly influenced by it. Understanding scalar excitations is at the same time, in some way, an understanding of the vacuum properties of the corresponding theory which is a particularly difficult task in the case it has an strongly coupled regime.

In this talk I will summarize our work on scalar mesons in low energy QCD. The well-established lowest lying scalar mesons are the isovector $a_0(980)$ and the isoscalar $f_0(980)$. These mesons are nearly degenerate in mass which suggests they are the scalar analogous to the $\rho(770)$ and $\omega(780)$ which would imply a $\frac{1}{\sqrt{2}}(\bar{u}u - \bar{d}d)$ and $\frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d)$ for the $a_0(980)$ and $f_0(980)$ respectively. The first problem with this identification is the experimental fact that the $f_0(980)$ strongly couples to the $\bar{K}K$ system. The second problem is the small coupling to two photons these mesons have, a problem which we will review in detail below. Before this let us mention that over the past few years compelling evidence has accumulated for the existence of a broad isoscalar structure (σ) in the very low energy region [1] which is strongly coupled to two pions and the existence of a isospinor scalar in the 800 – 900 MeV has been claimed by many authors [2], although its existence is still under debate [3].

A. Scalar (and pseudoscalar) mesons as $\bar{Q}Q$ states: testing the structure of hadrons with photons.

Electromagnetic decays of hadrons give valuable information on their structure for the simple reason that photons couple to charged objects, in particular to the partons constituting a hadron. In this sense the two photon decay of scalars constitute direct evidence for their quark structure. Quark model calculations for the $a_0(980) \rightarrow \gamma\gamma$ and $f_0(980) \rightarrow \gamma\gamma$ decays were summarized in [4] and a molecule structure was explored in this work which seemed to be favored by the measured branching ratios. Here we will work with the following assumptions: i) meson are composed of $\bar{Q}Q$ where Q denotes a **constituent** (colored) quark. ii) They are non-relativistic systems and we work in the zero-binding approximation ($M \approx 2m_Q$). Under these assumptions we can use either NRQCD-like calculations (singlet channels only) or we can apply the quarkonium techniques developed in [5]. The calculations lead to

$$\begin{aligned}\Gamma(^1S_0 \rightarrow \gamma\gamma) &= \frac{12\alpha^2}{M_P^2} |R(0)|^2 e_Q^2 \\ \Gamma(^3P_J \rightarrow \gamma\gamma) &= \frac{N_J \alpha^2}{M_J^4} |R'(0)|^2 e_Q^2\end{aligned}$$

where $N_0 = 432$, $N_2 = 576/5$ and $N_1 = 0$ as required by charge conjugation. Here, e_Q denotes the charge of the constituent quark (in units of e) and $R(0)$, $R'(0)$ denote the quarkonium wave function and its derivative evaluated at the origin respectively. For the physical process $meson \rightarrow \gamma\gamma$ it is necessary to consider the isospin structure which amounts to replace $e_Q^2 \rightarrow F(I)$, where $F(1) = (e_u^2 - e_d^2)/\sqrt{2}$ for a $(\bar{u}u - \bar{d}d)/\sqrt{2}$ meson and $F(0) = (e_u^2 + e_d^2)/\sqrt{2}$ for a $(\bar{u}u + \bar{d}d)/\sqrt{2}$ meson. The only unknown parameters here are the wave functions at the origin which do not allow us to predict the individual widths. However, this factor cancels out in the ratios of widths which allow us to compare with the measured ratios for mesons with the same orbital angular momentum. We show in a table the results for the ratios of different combinations of the $^3P_J \rightarrow \gamma\gamma$ decay widths $R_{th}^{M_1 M_2} \equiv \frac{\Gamma(M_1 \rightarrow \gamma\gamma)}{\Gamma(M_2 \rightarrow \gamma\gamma)} = \left(\frac{m_{M_2}}{m_{M_1}}\right)^4 \frac{F^2(I_1)}{F^2(I_2)}$. In this table a $(\bar{u}u + \bar{d}d)/\sqrt{2}$ structure has been assumed for the f_0 and f_2 mesons and a $(\bar{u}u - \bar{d}d)/\sqrt{2}$ structure for the a_0 and a_2 mesons.

$M_1 M_2$	$R_{th}^{M_1 M_2}$	$R_{exp}^{M_1 M_2}$
$a_2(1320)f_2(1270)$	0.31	0.36 ± 0.05
$a_0(980)f_0(980)$	0.35	1.62 ± 0.96
$f_0(980)f_2(1270)$	0.76	0.14 ± 0.04
$a_0(980)a_2(980)$	0.85	0.24 ± 0.09

The conclusion we extract from this table is that two photon decays of tensor mesons are consistent with the assumed composition whereas $a_0(980) \rightarrow \gamma\gamma$ **and** $f_0(980) \rightarrow \gamma\gamma$ **are not consistent with a $(\bar{u}u \pm \bar{d}d)/\sqrt{2}$ structure for these mesons.** Another possibility in the case of the $f_0(980)$ is a $\bar{s}s$ structure. For this case we obtain $R_{th}^{f_0 f_2} = 0.06$ vs $R_{exp}^{f_0 f_2} = 0.14 \pm 0.04$. Thus $f_0(980) \rightarrow \gamma\gamma$ is neither well described in terms of quarkonium calculations assuming a pure $\bar{s}s$ structure. It still remain the possibility that the $f_0(980)$ be a more complicated object similar to the η or η' i.e. $f_0 = \sin \phi_s S_{ns} + \cos \phi_s S_s$ where $S_{ns} = (\bar{u}u +$

$\bar{d}d)/\sqrt{2}$ and $S_s = \bar{s}s$. In this case $R_{th}^{f_0 f_2} = \frac{4}{15}(\frac{M_{f_2}}{M_{f_0}})^4(\sin \phi_s + \frac{\sqrt{2}}{5} \cos \phi_s)$ and agreement with the experimental ratio requires $\phi_s \approx 9^\circ$.

What about pseudoscalars?. In this case the quarkonium state has the $J^{PC} = 0^{-+}$ quantum numbers (1S_0 state in spectroscopic notation). The predicted ratio of widths in the case $\eta - \pi$, written in terms of the mixing angle in the singlet-octet basis $\theta_P = \phi_P - 54.7^\circ$ is $R_{th}^{\eta\pi} = \frac{m_\eta^3}{m_\pi^3}(\frac{m_\pi}{m_\eta})^5 \frac{1}{\sqrt{3}}[\cos \theta_P - 2\sqrt{2} \sin \theta_P]^2$. In this case, the results for the ratio of widths differ from those arising in naive quark model (or SU(3)) (see e.g. [6] page 117). Indeed, there is a dynamical factor $(\frac{m_\pi}{m_\eta})^5 \approx 10^{-3}$ for this ratio which considerably reduce the ratio with respect to naive quark model considerations when physical masses are used in the numerics. Reproducing experimental data require to introduce a “reference mass” (M_R) [7] whose origin is clear in our framework, $M_R \approx 2m_Q$ which represent the “constituent mass” for the quarkonium. The inability of quarkonium calculations to describe two photon decays of pseudoscalars without any additional assumption has to do with the mechanisms which deviate the values of the masses of pseudoscalars from their “constituent mass” values. It has been clear since the early days of QCD that the spectrum of pseudoscalars is strongly influenced by non-trivial effects due to the properties of the QCD vacuum. On the other hand scalars have the same quantum numbers as the vacuum and the immediate question is whether or not the scalar spectrum and decay properties are modified, from what we naively would expect, by effects due to the properties of the QCD vacuum. In the next section we will review our work on the effects of the vacuum in the structuring of the spectrum and decay properties of scalar mesons.

B. Chiral symmetry, vacuum effects and scalar meson properties.

We explored this topic in the framework of a Linear Sigma Model (LSM) which incorporates the most important effects in the low energy domain of QCD, namely, the spontaneous breaking of chiral symmetry (SB χ S) and the breakdown of the singlet axial symmetry. For the latter we use the bosonized version of the instanton induced six-quark interaction discovered by 't Hooft. The pseudoscalar and scalar matrix fields P and σ are written in terms of a specific basis spanned by seven of the standard Gell-Mann matrices, namely λ_i ($i = 1, \dots, 7$), and by two unconventional matrices $\lambda_{ns} = \text{diag}(1, 1, 0)$, and $\lambda_s = \sqrt{2} \text{diag}(0, 0, 1)$, respectively. We use the convention $P \equiv \frac{1}{\sqrt{2}} \lambda_i P_i$ with $i = ns, s, 1, \dots, 7$ and similarly for the scalar field. The scalar and a pseudoscalar mesonic nonet enter in the chiral combination $M = \sigma + iP$. The lagrangian is

$$\mathcal{L} = \mathcal{L}_{sym} + \mathcal{L}_{U_A(1)} + \mathcal{L}_{SB}. \quad (1)$$

The $[U(3)_L \otimes U(3)_R]$ symmetric part is given by

$$\mathcal{L}_{sym} = \frac{1}{2} \text{tr} [(\partial_\mu M)(\partial^\mu M^\dagger)] - \frac{\mu^2}{2} X(\sigma, P) - \frac{\lambda}{4} Y(\sigma, P) - \frac{\lambda'}{4} X^2(\sigma, P), \quad (2)$$

where $X(\sigma, P) \equiv \text{tr} [MM^\dagger]$ $Y(\sigma, P) \equiv \text{tr} [(MM^\dagger)^2]$. The $U_A(1)$ symmetry breaking lagrangian is given by $\mathcal{L}_{U_A(1)} = -\beta \{\det(M) + \det(M^\dagger)\}$. Finally we have the explicit symmetry breaking term $\mathcal{L}_{SB} = \text{tr} [c\sigma] = \text{tr} [\frac{b_0}{\sqrt{2}} \mathcal{M}_q (M + M^\dagger)]$ where $c \equiv \frac{1}{\sqrt{2}} \lambda_i c_i$, is related to the quark

mass matrix \mathcal{M}_q by $c = \sqrt{2}b_0\mathcal{M}_q$ and has $\frac{c_{\text{ns}}}{\sqrt{2}} = \sqrt{2}\hat{m}b_0$ and $c_s = \sqrt{2}m_sb_0$ as the only non-vanishing entries. Here, b_0 is an unknown parameter with dimensions of squared mass. We work in the exact isospin limit, $\hat{m} = m_u = m_d$. The linear σ term induces σ -vacuum transitions which rearrange the vacuum. Shifting to physical fields we obtain the following masses [8–12] :

$$\begin{aligned}
m_\pi^2 &= \xi + \underline{2\beta b} + \lambda a^2, & m_{a_0}^2 &= \xi - \underline{2\beta b} + 3\lambda a^2 \\
m_K^2 &= \xi + \underline{2\beta a} + \lambda(a^2 - ab + b^2), & m_\kappa^2 &= \xi - \underline{2\beta a} + \lambda(a^2 + ab + b^2) \\
m_{\eta_{\text{ns}}}^2 &= \xi - \underline{2\beta b} + \lambda a^2, & m_{S_{\text{ns}}}^2 &= \xi + \underline{2\beta b} + 3\lambda a^2 + 4\lambda' a^2, \\
m_{\eta_s}^2 &= \xi + \lambda b^2, & m_{S_s}^2 &= \xi + 3\lambda b^2 + 2\lambda' b^2 \\
m_{\eta_{\text{s-ns}}}^2 &= \underline{-2\sqrt{2}\beta a}, & m_{S_{\text{s-ns}}}^2 &= \underline{2\sqrt{2}(\beta + \lambda'b)} \underline{a}.
\end{aligned} \tag{3}$$

where $a = \langle \sigma_{\text{ns}} \rangle / \sqrt{2}$, $b = \langle \sigma_s \rangle$ and $m_{\eta_{\text{s-ns}}}^2$, $m_{S_{\text{s-ns}}}^2$ denote the OZI rule violating terms mixing strange and non-strange isoscalar quarkonia. Notice that the $U_A(1)$ symmetry breaking couples to the spontaneous breakdown of chiral symmetry (underlined terms in Eq.(3)) contributing to the masses of all fields (except strange fields) and this effect has the opposite sign in the scalar sector with respect to the pseudoscalar sector. In particular it is responsible for the mixing of flavor fields. We claim that this is the striking effect which explains the unusual properties of the lowest lying scalar mesons. In [8,9] the corresponding coupling has been fixed to $\beta = -1.551 \pm 0.072$ GeV using information on the pseudoscalar spectrum as input and the members of the scalar nonet were identified as $\sigma(\approx 450)$, $f_0(980)$, $a_0(980)$, and $\kappa(\approx 900)$. The $U_A(1)$ -SB χ S effect has the following consequences: It pushes the pions and kaons **down** making them light (an effect driven by the quark masses since elimination of linear terms after SB χ S requires $f_\pi m_\pi^2 = 2\hat{m}b_0$; $f_K m_K^2 = (\hat{m} + m_s)b_0$) and the η_{ns} **up** making it heavy (an effect only partly driven by quark masses).ii) It pushes the a_0 and κ mesons **up** making them heavy and σ_{ns} **down** making it light. As a consequence this effect simultaneously explains at the qualitative level :i) Why the pion and kaon are light, ii) The mixing of pseudoscalar and scalar mesons. iii) Why the η_{ns} is so heavy, iv) Why the sigma meson is so light, vi) The accidental degeneracy of the $a_0(980)$ and the $f_0(980)$ (and perhaps also of the κ meson) vi) The strong coupling of the $f_0(980)$ to $\bar{K}K$. The immediate question at this point is what the model predicts for the coupling of $f_0(980)$ and $a_0(980)$ to two photons.

C. Consistent description of $a_0(980) \rightarrow \gamma\gamma$ and $f_0(980) \rightarrow \gamma\gamma$ decays

The $a_0(980) \rightarrow \gamma\gamma$ and $f_0(980) \rightarrow \gamma\gamma$ decays have been calculated in the present framework [13]. These decays are induced by loops of charged mesons (M). The calculation of the corresponding diagrams give *finite* contributions. The analytical results depend on the

SMM couplings which are related to meson masses by chiral symmetry. The amplitude for $S \rightarrow \gamma\gamma$ decay is

$$\mathcal{M}(S \rightarrow \gamma(\varepsilon, k)\gamma(q, \eta)) = \frac{i\alpha}{\pi f_K} \mathcal{A}^S(q.k g^{\mu\nu} - k^\mu q^\nu) \eta_\mu \varepsilon_\nu. \quad (4)$$

and the corresponding width is $\Gamma(S \rightarrow \gamma\gamma) = \frac{\alpha^2}{64\pi^3} \frac{m_S^3}{f_K^2} |\mathcal{A}^S|^2$, whereas the measured widths are [6] $\Gamma(f_0 \rightarrow \gamma\gamma)_{exp} = 0.39_{-13}^{+10}$ keV, $\Gamma(a_0 \rightarrow \gamma\gamma)_{exp} = 0.24_{-0.07}^{+0.08}$ keV (we assume $BR(a_0(980) \rightarrow \pi^0\eta) \cong 1$). From these values we extract $|\mathcal{A}_{exp}^{a_0}| = 0.34 \pm 0.05$ and $|\mathcal{A}_{exp}^{f_0}| = 0.44 \pm 0.07$.

In the model, the $a_0 \rightarrow \gamma\gamma$ decay is induced by loops of kaons and kappas. Kaon loops yield $\mathcal{A}_K^{a_0} = 0.42$. Kappa loops interfere destructively with kaon loops and results depend on the kappa mass. Using e.g. $m_\kappa = 900$ MeV we obtain $\mathcal{A}_{LSM}^{a_0} = 0.36$. The experimental result is consistent with $m_\kappa \in [800, 935]$ MeV.

In the case of the $f_0(980) \rightarrow \gamma\gamma$ decay there are contributions from loops of pions kaons and kappas. The corresponding amplitudes as calculated in the model yield $\mathcal{A}_M^{f_0} = f_K \left(\frac{g_{f_0 MM}}{m_f^2} \right) N_M$ with the loop factors $N_\pi = (-1.10 + 0.48i)$, $N_K = 1.06$ and the value of N_κ depend again on the kappa mass. For $m_\kappa = 900$ MeV we obtain $N_\kappa = 0.12$. The dominant contribution again comes from kaon loops since the $f_0\pi\pi$ coupling is proportional to the $\sin\phi_s$ factor which is small, and the $f_0\kappa\kappa$ coupling is proportional to $m_f^2 - m_\kappa^2$ which is also small relative to the typical hadron energy scale of 1 GeV. Kaon loops contributions alone (using $\phi_s = -9^\circ$) yield $\mathcal{A}_K^{f_0} = 0.46$ whereas including all contributions (using the E791 value $m_\kappa = 797$ MeV [23]) yield $|\mathcal{A}_{LSM}^{f_0}| = 0.42$ to be compared with $|\mathcal{A}_{exp}^{f_0}| = 0.44 \pm 0.06$. Reversing the argument: fixing the value of m_κ to the central value of E791, the experimental uncertainties allow for $\phi_s \in [-4^\circ, -25^\circ]$. In the whole we conclude that experimental data on $a_0 \rightarrow \gamma\gamma$ and $f_0 \rightarrow \gamma\gamma$ are well described by meson loops.

D. Complementarity of LSM and χ PT in the scalar channel: $V^0 \rightarrow P^0 P^{0'} \gamma$ decays.

From the experimental point of view these decays are a clean place to study $P^0 - P^{0'}$ systems since neutral particles are involved in the final state, hence there exist no final state radiation. Branching ratios and energy spectrum were recently measured for some of these decays by the SND and CMD collaborations at Novosibirsk and improved data can be expected from DAΦNE. On the theoretical side contributions from intermediate vector mesons $V^0 \rightarrow V^{0'} P^0 \rightarrow P^0 P^{0'} \gamma$ were estimated in [14] using VMD and the corresponding results do not describe the experimental results for the BR.'s. The possibility of enhancement of these BR's due to re-scattering effects was explored in [15] using χ PT with vector mesons as external fields. At leading order ($\mathcal{O}(p^4)$) these contributions are **finite** and no ambiguities due to counter-terms exist. VMD and chiral loops contributions are collected in a table below which shows that these contributions do not account for the measured BR's either. Since the $P^0 - P^{0'}$ system can be in a $J^P = 0^+$ state we should expect resonant effects due to scalars manifest in these decays.

Decay	$BR_{\text{exp}} \times 10^5$	$(VC) \times 10^5$	$(\chi\text{PT}) \times 10^5$
$\phi \rightarrow \pi^0 \pi^0 \gamma$	$11.58 \pm 0.93 \pm 0.52$	1.2	5.05
$\phi \rightarrow \pi^0 \eta \gamma$	$9.0 \pm 2.4 \pm 1.0$	0.54	2.95
$\phi \rightarrow K^0 \bar{K}^0 \gamma$		2.7×10^{-7}	1.0×10^{-3}
$\rho \rightarrow \pi^0 \pi^0 \gamma$	$4.2^{+2.9}_{-2.0} \pm 1.0$	1.1	0.97
$\rho \rightarrow \pi^0 \eta \gamma$		4×10^{-5}	4×10^{-6}
$\omega \rightarrow \pi^0 \pi^0 \gamma$	7.2 ± 2.5	2.8	9×10^{-2}
$\omega \rightarrow \pi^0 \eta \gamma$		1.6×10^{-2}	1.6×10^{-4}

Vector fields were introduced as external field in the model in [16–18] and contributions of intermediate scalar mesons to these processes were calculated for the most interesting processes, namely $\phi \rightarrow \pi^0 \pi^0 \gamma$, $\phi \rightarrow \pi^0 \eta \gamma$ and $\rho, \omega \rightarrow \pi^0 \pi^0 \gamma$. We refer to [16–18] for details. Here we just summarize the main results. From the theoretical point of view is worth to remark that the obtained amplitudes to these processes reduce to the $\mathcal{O}(p^4)$ χPT amplitudes obtained in [15] in the case of heavy scalars. In this sense, LSM yields results which are complementary to χPT . In addition to catch the physics of chiral loops the LSM amplitude is also able to reproduce the effects of the scalar poles at higher $P^0 P^{0'}$ invariant mass values. In the case of $\phi \rightarrow P^0 P^{0'} \gamma$ pion loops are suppressed by G-parity, hence kaon loops give the most important contribution. The decay $\phi \rightarrow \pi^0 \pi^0 \gamma$ is highly sensitive to the scalar mixing angle and it is not sensitive to the σ mass whenever it be light since $g_{\sigma KK} \sim m_\sigma^2 - m_K^2$. Disastrous results are obtained for $m_\sigma > 600$ MeV. The energy spectrum for this process is nicely reproduced by the calculations in the model [16]. The calculated branching ratios, including intermediate vector meson contributions is $BR(\phi \rightarrow \pi^0 \pi^0 \gamma)_{\text{TH}} = 1.08 \times 10^{-4}$ which is to be compared with $BR(\phi \rightarrow \pi^0 \pi^0 \gamma)_{\text{EXP}} = 1.08 \pm 0.17 \pm 0.09$ measured by the CMD2 coll. [19] and $BR(\phi \rightarrow \pi^0 \pi^0 \gamma)_{\text{EXP}} = 1.14 \pm 0.10 \pm 0.12$ obtained by the SND Coll. [20].

In the case of $\phi \rightarrow \pi^0 \eta \gamma$, the only intermediate scalar is the $a_0(980)$ [17]. The corresponding spectrum is also reproduced in the model. The branching ratio calculated in the model is $B(\phi \rightarrow \pi^0 \eta \gamma)_{\text{LSM}} = (0.75\text{--}0.95) \times 10^{-4}$, to be compared with the values reported by the CMD2 Collaboration $B(\phi \rightarrow \pi^0 \eta \gamma)_{\text{CMD2}} = (0.90 \pm 0.24 \pm 0.10) \times 10^{-4}$ [19] and the SND result $B(\phi \rightarrow \pi^0 \eta \gamma)_{\text{SND}} = (0.88 \pm 0.14 \pm 0.09) \times 10^{-4}$ [21]. Improved data near the a_0 pole will be very important in the understanding of the $a_0(980)$ meson.

In the case of $\rho \rightarrow \pi^0 \pi^0 \gamma$ exchange of vector mesons account for $\approx 25\%$ of the measured BR, χral loops (dominated by pions) account for another $\approx 20\%$ and the calculated BR taking into account both contributions [15] is within two standard deviations from the experimental results recently reported by the SND Coll. [21] and quoted in table above. An analysis of the energy spectrum as a function of the mass and width of the σ meson shows that this process is sensitive enough to these quantities and a measurement of the spectrum can be used to extract the corresponding values. Integrating the $\pi^0 \pi^0$ invariant mass spectrum and using the central values obtained by the E791 Collaboration $m_\sigma = 478^{+24}_{-23} \pm 17$ MeV and $\Gamma_\sigma = 324^{+42}_{-40} \pm 21$ MeV we obtain $BR(\rho \rightarrow \pi^0 \pi^0 \gamma)_{\text{LSM}} = 1.5 \times 10^{-5}$. For $m_\sigma = 478$ MeV and a narrower width $\Gamma_\sigma = 263$ MeV (as predicted by the LSM, see also [24]) we obtain $BR(\rho \rightarrow \pi^0 \pi^0 \gamma)_{\text{LSM}} = 2.1 \times 10^{-5}$.

Finally, in the case of $\omega \rightarrow \pi^0 \pi^0 \gamma$ pion loops are also suppressed by G-parity and kaon loops should give the most important contribution. However, the intermediate scalars are $f_0(980)$ and σ and the $f_0(980)$ has a large mass compared to the energy region of interest

whereas σ contributions are highly suppressed since $g_{\sigma KK} \sim m_\sigma^2 - m_K^2$. Hence, whenever the mass of the sigma meson be small, scalar effects are negligible in this process, although interference with the intermediate vector meson contributions seem to close the gap between the experimental results $BR(\omega \rightarrow \pi^0 \pi^0 \gamma)_{\text{EXP}} = (7.2 \pm 2.5) \times 10^{-5}$ [6] and the VM contributions when we take care of including properly the $\omega - \rho$ mixing [18] which yield $BR(\omega \rightarrow \pi^0 \pi^0 \gamma)_{\text{TH}} = 4.5 \pm 1.1 \times 10^{-5}$ [18] (see also [25]).

E. Conclusions.

Summarizing, calculations for $S \rightarrow \gamma\gamma$ ($S = a_0(980), f_0(980)$) considering S as a NR-quarkonium state yield results which are not consistent with experimental data. The same is true in the case of pseudoscalars. In this case the disagreement can be traced back to the strong distortion of the spectrum from naive quarkonium expectations due to QCD vacuum effects. Since scalars have the same quantum numbers as the vacuum, highly non-trivial effects are expected in this sector due to vacuum properties. We study such effects in the framework of a phenomenological $U(3) \times U(3)$ chiral lagrangian which incorporates spontaneous χS and $U_A(1)$ symmetry breaking. In this framework there is an important effect: the coupling of the $U_A(1)$ violating interaction to the spontaneous breaking of chiral symmetry which generates mass terms ($U_A(1)$ -SB χS effect). This effect simultaneously explains: the smallness of the masses of the pions and kaons (an effect driven by quark masses), the OZI-rule violating mixing of flavor fields, the accidental degeneracy of the $a_0(980)$ and $f_0(980)$, the lightness of the sigma meson and the controversial $a_0, f_0 \rightarrow \gamma\gamma$ decays. Intermediate scalar contributions to $V^0 \rightarrow P^0 P'^0 \gamma$ are also calculated. The energy spectrum of $\phi \rightarrow \pi^0 \pi^0 \gamma$ is nicely described giving direct evidence for the assignment of the $f_0(980)$ and indirect evidence for a light σ . Calculations for total and partial BR's are in good agreement with measurements from SND and CMD collaborations. Energy spectrum in $\phi \rightarrow \pi^0 \eta \gamma$ is well described by the chiral loops + scalar resonant effects. Improvement in the measurements near the a_0 pole are encouraged. We also calculate the $\rho \rightarrow \pi^0 \pi^0 \gamma$ decay. The corresponding BR is sensitive to the parameters of the σ . The branching ratio as measured by the SND Coll. is consistent with the results of the model when the values for the mass and width of this scalar as measured by the E791 Collaboration are used. Measurements of the energy spectrum are encouraged. Finally, $\omega \rightarrow \pi^0 \pi^0 \gamma$ is not sensitive to scalar contributions.

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REFERENCES

- [1] See e.g. N. A. Tornqvist, “Summary talk of the conference on the sigma resonance,” Kyoto, Japan, June (2000). arXiv:hep-ph/0008135. N. A. Tornqvist, “Does the light and broad sigma(500) exist?,” arXiv:hep-ph/9904346 and references therein.
- [2] R. L. Jaffe, The Phenomenology Of (2 Quark 2 Anti-Quark) Mesons,” Phys. Rev. D **15**, 267 (1977). R. L. Jaffe, Phys. Rev. D **15**, 281 (1977).
M. D. Scadron, Phys. Rev. D **26**, 239 (1982).
E. Van Beveren, T. A. Rijken, K. Metzger, C. Dullemond, G. Rupp and J. E. Ribeiro, Z. Phys. C **30**, 615 (1986).
S. Ishida, M. Ishida, T. Ishida, K. Takamatsu and T. Tsuru, Prog. Theor. Phys. **98**, 621 (1997) [arXiv:hep-ph/9705437].
D. Black, A. H. Fariborz, F. Sannino and J. Schechter, Phys. Rev. D **58**, 054012 (1998) [arXiv:hep-ph/9804273].
J. A. Oller and E. Oset, Phys. Rev. D **60**, 074023 (1999) [arXiv:hep-ph/9809337].
- [3] S. N. Cherry and M. R. Pennington, Nucl. Phys. A **688**, 823 (2001) [arXiv:hep-ph/0005208]. S. Cherry and M. R. Pennington, arXiv:hep-ph/0007275.
- [4] T. Barnes, Phys. Lett. B **165**, 434 (1985).
- [5] J. H. Kuhn, J. Kaplan and E. G. Safiani, Nucl. Phys. B **157**, 125 (1979). J. G. Korner, J. H. Kuhn, M. Krammer and H. Schneider, Nucl. Phys. B **229**, 115 (1983). R. Barbieri, R. Gatto and R. Kogerler, Phys. Lett. B **60**, 183 (1976).
- [6] D. E. Groom *et al.* [Particle Data Group Collaboration], Eur. Phys. J. C **15**, 1 (2000).
- [7] C. Hayne and N. Isgur, Phys. Rev. D **25**, 1944 (1982).
E. S. Ackleh and T. Barnes, Phys. Rev. D **45**, 232 (1992).
- [8] M. Napsuciale, arXiv:hep-ph/9803396.
- [9] M. Napsuciale, A. Wirzba and M. Kirchbach, arXiv:nucl-th/0105055, to appear in Nucl. Phys. A.
- [10] M. Napsuciale and S. Rodriguez, Int. J. Mod. Phys. A **16**, 3011 (2001).
- [11] N. A. Tornqvist, Eur. Phys. J. C **11**, 359 (1999) [arXiv:hep-ph/9905282].
- [12] G. ’t Hooft, arXiv:hep-th/9903189.
- [13] J. L. Lucio Martinez and M. Napsuciale, Phys. Lett. B **454**, 365 (1999) [arXiv:hep-ph/9903234].
- [14] A. Bramon, A. Grau and G. Pancheri, Phys. Lett. B **283**, 416 (1992).
- [15] A. Bramon, A. Grau and G. Pancheri, Phys. Lett. B **289**, 97 (1992).
- [16] J. L. Lucio and M. Napsuciale, *Proceedings of the III International Workshop on Physics and Detectors for DaΦne*, edited by S. Bianco *et al.* (Frascati Physics Series Vol. XVI 2000), p. 591 arXiv:hep-ph/0001136.
- [17] A. Bramon, R. Escribano, J. L. Lucio M., M. Napsuciale and G. Pancheri, Phys. Lett. B **494**, 221 (2000) [arXiv:hep-ph/0008188].
- [18] A. Bramon, R. Escribano, J. L. Lucio Martinez and M. Napsuciale, Phys. Lett. B **517**, 345 (2001) [arXiv:hep-ph/0105179].
- [19] R. R. Akhmetshin *et al.* [CMD-2 Collaboration], Phys. Lett. B **462**, 380 (1999) [arXiv:hep-ex/9907006].
- [20] V. M. Aulchenko *et al.* [SND Collaboration], Phys. Lett. B **440**, 442 (1998) [arXiv:hep-ex/9807016].

- [21] M. N. Achasov *et al.*, JETP Lett. **71**, 355 (2000) [Pisma Zh. Eksp. Teor. Fiz. **71**, 355 (2000)].
- [22] E. M. Aitala *et al.* [E791 Collaboration], Phys. Rev. Lett. **86**, 770 (2001) [hep-ex/0007028].
- [23] C. Gobel [E791 Collaboration], arXiv:hep-ex/0110052.
- [24] N. Wu, arXiv:hep-ex/0104050.
- [25] D. Guetta and P. Singer, Phys. Rev. D **63**, 017502 (2001) [arXiv:hep-ph/0005059].